

**SOLID WASTE ASSOCIATION OF NORTH AMERICA (SWANA)  
CONFERENCE, ST. LOUIS, MISSOURI, U.S.A. OCTOBER 2003  
“WasteCon 2003”**

**Published on the Proceedings, Pages 290-296**

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**OPERATIONAL FULL-SCALE ARROWBIO PLANT INTEGRATES  
SEPARATION AND ANAEROBIC DIGESTION IN WATERY PROCESSING,  
WITH NEAR-ZERO LANDFILLING**

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**ABSTRACT**

The ArrowBio Process<sup>1,2</sup> recovers over 90% of the material and energy resources from mixed Municipal Solid Waste (MSW), leaving less than 10% to be landfilled.

At the outset of processing, the packer truck tips the load directly into water in a special purpose vat. The functions of water, abetted by bag breaker, slow speed shredder, hydraulic shear, and partitioning trommel screen devices, are two-fold. One is to serve as a fluid in the gravitational separation of non-biodegradable and biodegradable substances. (The buoyancy of water gives much better separation compared to air.) Water's other function is to

prepare the biodegradable materials for advanced anaerobic digestion, in that soluble substances come into solution and particulate organics become soggy and easily fragmented.

The anaerobic digestion method employed, for its superior kinetic and thermodynamic properties (speed and thoroughness of biological action), is the variant known as Upflow Anaerobic Sludge Blanket (UASB) digestion. This variant requires a watery feedstock. It produces biogas unusually rich in methane, in a quantity greatly exceeding internal power needs. Excess digester culture (“solids”) is highly stabilized and usable as a soil conditioner without further treatment. Moreover, the digestion liberates the moisture in the MSW, providing liquid water in excess of processing needs.

A one module (~70,000 ton per year) ArrowBio facility is operational at the Tel Aviv, Israel, transfer station. Its footprint is approximately 2 acres. Almost all of the equipment is standard “off-the-shelf,” and structural components such as vats and bioreactor vessels would be fabricated locally. Since processing is at biological temperatures and ambient pressures (no high temperature/pressure vessels), the system is relatively uncomplicated, safe, and low in cost. Construction time is about one year. A multi-factor comparison with other anaerobic digestion technologies, and with incineration, pyrolysis/gasification, composting and landfilling, indicates significant advantages for the ArrowBio Process (see later).

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<sup>1</sup> The ArrowBio Process, which holds a United States patent, is a development of Arrow Ecology Ltd., Haifa, Israel.

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## VIEW OF THE ARROWBIO PLANT IN OPERATION

This presentation at the WasteCon 2003 conference opens with a four-minute CD video showing the ArrowBio Process in operation. The subject facility, located at the Tel Aviv, Israel, transfer station, consists of a single module capable of processing approximately 70,000 tons per year of mixed municipal solid waste (MSW). It culminates a nine-year developmental program that progressed through laboratory, pilot, and small commercial stages. The full-scale plant was started up in January 2003 and is now (July 2003) fully operational.

Still photos of the plant may be viewed at [www.arrowbio.com](http://www.arrowbio.com). A more detailed, pictorial, description of the underlying logic of the ArrowBio Process and its technical implementation is scheduled for publication in early 2004 in *MSW Management* (SWANA publication).

## WATER IN MSW – ORDINARILY A PROBLEM

A major proportion of MSW consists of water, mostly entrained in the biodegradable organic fraction. While moisture contents vary widely, for general purposes a value of 30% may be taken as being reasonably representative for mixed MSW (**APPENDIX I**). With a substantial source separation of impervious (glass, metal, plastic) and relatively dry (paper products) materials for recycling, the remainder, still the bulk of the waste stream, is wetter in being dominated by food and vegetative wastes. Such a mixture might have a moisture content of 40% or more. Thus, a ton of MSW may contain some 600 to 800 pounds of water.

Ordinarily, the moisture content of MSW causes difficulties. It interferes with the recovery of traditional recyclables such as containers from mixtures not entirely free of organics. In the “dry tomb” landfill, though not in the “bioreactor” variant, the less moisture the better. In combustion (incineration) and other thermal processes (pyrolysis/gasification), the water in MSW detracts from the energy yield. At the start of a composting cycle, depending on the feedstock’s moisture content, it may be necessary either to add water, or to reduce the moisture content by blending in drier material. Since drying occurs during composting (evaporative cooling is the main mechanism of heat removal), the addition of water may be necessary to maintain biological activity. In the anaerobic digestion of MSW organics as usually practiced, water addition with stirring is necessary at the outset to make a thick slurry. Later, water must be removed mechanically

from the slurry to make the partially stabilized residual organics manageable. .

In all of these methods, at various operational points, the weight of the water in the MSW aggravates the problem of materials handling and otherwise hinders manipulation. In many respects water is an invisible, and because of its ubiquity, often under-appreciated constraint on MSW operations.

## ARROWBIO’S UNIQUE RELATIONSHIP TO WATER

### Physical Separation/Preparation Phase of Processing

In notable contrast, the ArrowBio Process frankly exploits the properties of water to good effect. Thus, processing in its major components, physical separation and preparation, and biological treatment, is watery. At the same time the water needed for processing is derived from the moisture content of the MSW, without need for external supply.

As seen in the CD video shown at the outset of this presentation, processing begins by tipping the load directly from the packer truck into water circulating in a purpose-built vat. Three immediate “side-benefits” are that dust is eliminated, odors quenched, and subsequent materials handling eased. Whereas MSW in its usual solid form is moved with difficulty, in flowing water it is moved with ease.

While these benefits are important, the fundamental purpose of tipping into water is to initiate the separation and preparation functions underlying the overall process. Thus, gravitational separation *in water* is brought into play. Owing to its buoyancy, water is a far more effective separation fluid than air. And two other properties of water come into play, serving to prepare biodegradable materials for advanced anaerobic digestion. These are that water brings soluble organics into solution, while also soaking and weakening the solid phase materials so they are easily fragmented. Non-soluble biodegradables are finally reduced to a fine suspension.

The above three agencies (gravitational separation in water, dissolution in water, permeation of water) are aided by the following devices: a bag beaker, a slow speed shredder, a hydraulic shear, partitioning trommel screens. Throughout the separation/preparation phase of processing, the flow is deliberately convoluted and includes feedback loops. Thereby, the agencies are given multiple opportunities to complete their work. The end result is the effective separation of the non-biodegradable

(i.e., “recyclables”) and biodegradable fractions, and the preparation of the biodegradables for biological treatment.

The fate of different materials in the separation/preparation phase of processing is illustrated in the following examples:

*Soluble substances.* Materials that are soluble, as in foodstuffs, simply dissolve in the water.

*Containers that fill with water.* Since the water in the vat is in circulation (interchange with biological component) and agitated, containers tend to be swamped and sink to the floor of the vat. These, along with other “sinks,” are conveyed out of the vat to be cleansed in a spray of clean water (from biological component) and sorted. Sorting is via magnetic pickup, eddy current separation, and manual picking.

*Containers that do not fill with water.* Narrow-neck containers such as plastic soda bottles may not fill with water, but remain afloat. These may be removed by vacuum and then reunited with the sinks. Alternatively, floaters may encounter the slow speed shredder to be crushed or fragmented, destroying buoyancy and causing sinking.

*Film plastic.* Super market bags and other film plastic are removed pneumatically, for collection as a separate fraction of recyclable material.

*Unopened disposable diapers.* Diapers get disrupted at the bag breaker or elsewhere, and the contents dispersed according to their individual characteristics. Thus the outer sheet joins other film plastic, while the contents (feces, urine, wood and cottony fibers) dissolve or become waterlogged and ready for biological treatment.

*Insoluble biodegradable organic matter (e.g., paper products, watermelon rinds).* Such materials become waterlogged and progressively fragmented and macerated. Size-reduction continues until the particles pass as “unders” through a final trommel screen in the physical separation/preparation component of the plant.. Thus, only suitably prepared organics reach the biological component.

*‘Fines’/grit.* Small water non-absorbent particles settle in one of several settling tanks for removal from the system.

As separation/preparation proceeds, there is continuous pumping of ready material to the facility’s biological component. Half an hour after the last load of the day is tipped, the physical separation/preparation component is shut down for the day.

The products of the physical separation/preparation component are thus secondary raw materials (recyclables), a relatively small amount of biologically inert residue to be landfilled (~10%), and feedstock ready for biological treatment. Biological processing results in virtually no residual waste, thus recycling of about 90% of the input is recycled.

### **Biological Phase of Processing**

The prepared organic-rich flow, having a Biochemical Oxygen Demand (BOD) on the order of 20,000 mg/L, first enters acetogenic bioreactors for preliminary treatment. The partially treated flow then enters a bioreactor of the Upflow Anaerobic Sludge Blanket (UASB) type (**APPENDIX II**). This advanced form of anaerobic digestion is possible only in a watery system. Because of its kinetic (speed of microbial action) and thermodynamic (thoroughness of transformation to metabolic end-products) properties, UASB has become the preferred form of anaerobic digestion for strong wastewaters, for which it was originally intended. In effect the ArrowBio Process turns MSW organic solids into a strong wastewater, thereby making it possible to exploit the many advantages of UASB digestion.

The products of digestion are biogas (75% methane) in amounts roughly 5 x greater than needed to power the plant, excess culture (“solids”) ready for use as an organic soil amendment, and liquid water of which a portion is used to makeup losses in the plant’s physical component.

### **Seamless Match of Components**

The physical separation/preparation component thus supplies the biological component with a flow of organics ready to be metabolized. In turn, the biological component supplies the physical one with makeup water via continuous interchange between the two components. (The water in the separation/preparation vat is hardly stagnant.) Finally, the biological component powers the facility with its biogas product, while yet exporting the bulk of the power. The two components, physical and biological, thus form a seamless, mutually supportive whole.

## **THE ARROWBIO PROCESS IN PERSPECTIVE**

The main features of the ArrowBio Process are compared with those of other emerging technologies as well as with more established approaches to the management of MSW

(Table 1). The limitations of this analysis should be made explicit.

It is not possible for this analysis to be symmetrical. With respect to the ArrowBio Process, the entries are based on a specific proprietary process known in detail to the author. Otherwise, the references are to generic approaches based on publicly available information and general practice. The intent is to craft composite, least common denominator, general statements.

While this necessarily nonsymmetrical approach has its limitations, it might nonetheless provide a useful

thumbnail, first approximation, comparative overview of the constellation of available possibilities. Obviously, it cannot substitute for a detailed, unencumbered, comparison between, or among, specific proprietary systems. This would be the work of a demanding Request for Proposal (RFP).

**TABLE 1. MAJOR FEATURES OF DIFFERENT APPROACHES  
TO THE MANAGEMENT OF MUNICIPAL SOLID WASTE<sup>a</sup>**

<b>Factor or Function</b>	<b>ArrowBio Process</b>	<b>Other Anaerobic Digestion Processes</b>	<b>Pyrolysis/ Gasification<sup>b</sup></b>	<b>Incineration</b>	<b>Composting<sup>c</sup></b>	<b>Landfilling</b>
Basic driving force	Biological - UASB digestion <sup>d</sup>	Biological - anaerobic digestion of thick slurry	Thermo-chemical pyrolysis/O <sub>2</sub> -starved combustion	Combustion	Biological – aerobic self-heating	Biological - little or no process control
Moisture in MSW <sup>e</sup>	Not problematic	Problematic	Problematic	Problematic	Differs	Differs
Up-front separation of recyclables <sup>f</sup>	Intrinsic <sup>g</sup>	Extrinsic	Extrinsic	Extrinsic	Extrinsic	Extrinsic
Driving force speed	Fast	Intermediate <sup>h</sup>	Very fast	Very fast	Intermediate to slow <sup>i</sup>	Very slow
High pressures and/or temperatures	No	No	Yes <sup>j</sup>	Yes <sup>j</sup>	No <sup>k</sup>	No
Energy produced	Yes, biogas ~75% methane	Yes, biogas 50-60% methane	Yes, synthetic gas (syngas) mixture	Yes, heat used to make steam	No, consumed in process control (powering fans)	Yes, landfill gas (~ 50% methane) but only portion captured <sup>l</sup>
De-novo generation of hazardous/toxic compounds	No	No	Yes <sup>m</sup>	Yes <sup>m</sup>	No	No
Air emissions: prevention or control	Prevention	Prevention <sup>n</sup>	Control	Control	Control	Control
Track record	Short	Moderately lengthy	Short	Lengthy	Moderately lengthy	Very lengthy
Process residue	Stabilized organics (“mulch”)	Non-stabilized organics <sup>n</sup>	Char	Bottom and fly ash	Compost – stabilized?	N/A
Permitting difficulty/Public acceptability	More acceptable	More acceptable <sup>n,o</sup>	Less acceptable	Essentially not acceptable	Less acceptable <sup>o</sup>	Varies

See next for footnotes to Table 1.

<sup>a</sup> Limitations of analysis as well as its uses are noted in the text.

<sup>b</sup> Pyrolysis (destructive distillation) involves only O<sub>2</sub>-free reactions. Gasification can be seen as pyrolysis with an overlay of a small, metered, amount of O<sub>2</sub> supportive of combustion to a controlled extent.

<sup>c</sup> Refers to composting with purported process control (excludes passive “yard waste” variant).

<sup>d</sup> The UASB digestion follows an acetogenic stage (see Appendix II).

<sup>e</sup> See Appendix I.

<sup>f</sup> For example, separation of non-compliance containers from biodegradable organics. Separation may not be practiced in landfilling and other approaches.

<sup>g</sup> Intrinsic in that gravitational separation in water is part of the overall process. Where extrinsic a source of clean organics may be necessary, as in the anaerobic digestion of thick slurries of MSW organics.

<sup>h</sup> Problem of mass transport – see text and Appendix II.

<sup>i</sup> Not fast because process control is often deficient (c.f., Finstein, M.S. 1989. ASM News). See footnote **k**.

<sup>j</sup> e.g., Tens of atmospheres; temperatures of over 1,000°C.

<sup>k</sup> Optimum <60°C; usual maximum ~ 80°C (induces severe self-limitation), though spontaneous ignition possible.

<sup>l</sup> Even in the “bioreactor landfill” the escape of methane (greenhouse gas) over the dispersed area is unavoidable. It has been estimated that, at best, only about 2/3 of the gas can be captured <http://www.UNDP.org.in/programme/GEF/September/pages5-9.htm>.

<sup>m</sup> Gases generated in pyrolysis include carbon dioxide, carbon monoxide, hydrogen, and methane along with other more complex gaseous, liquid, and solid phase hydrocarbons. Such compounds are doubtless also formed in gasification, though they may be destroyed in the limited combustion supported by the metered injection of O<sub>2</sub>. In combustion (both incineration and gasification), dioxins and furans are formed. Some gasification technologies combat this by rapid cooling of the exhaust gas. This is not feasible in incineration, owing to the large volume of gas. Incinerators may be equipped with devices to trap the particulates bearing these compounds in the flue gas.

<sup>n</sup> Prevented in the anaerobic digestion process per se. However, the residual solids, owing to incomplete digestion, needs to be composted. Control of emissions from the composting varies.

<sup>o</sup> Composting has been plagued by odor nuisance problems, for reasons that are well understood but rarely fully incorporated into facility design (see footnote I).

#### **Table Commentary (inserted March 2004):**

This Table represents an attempt at a conceptual framework for discussion of major alternatives. Each entry is a complicated story in its own right deserving of critical evaluation against the available technologies being marketed. The table may be seen as a guide through the tangled thicket of MSW alternatives. It may be useful to you in your deliberations.

Columns 2, 3, and 4 are the most relevant to the decision being contemplated. Consider these approaches in reference to their **Basic driving**

**force**, which after all is the foundation for all else.

Consider **Moisture in MSW**. The ArrowBio Process is indifferent to the moisture content of the input, wet or dry, because it is watery throughout. Other systems may be affected by the moisture content and its variability.

**Up-front separation of recyclables**. This important operation is intrinsic to ArrowBio, in that water-based gravitational separation is

exploited. In other systems separation is extrinsic and based on usual air-based technologies.

**Driving force speed.** Pyrolysis/gasification is faster, followed in order by UASB digestion used in ArrowBio, and conventional digestion used elsewhere. Processing speed translates into the real issue - “footprint.” Even though pyrolysis/gasification *might* have a smaller footprint, this would hardly seem to compensate for its disadvantages.

**High pressures and/or temperatures.** Their absence is characteristic of biological processing in general. Their presence is problematic.

**Energy produced.** The biogas produce in UASB digestion is superior to that produced in conventional digestion, both qualitatively (higher methane content) and quantitatively (more gas). This superiority stems, basically, from the difference between the solids and hydraulic residence times characteristic of UASB digestion.

**De-novo generation of hazardous/toxic compounds.** Generation of hazardous/toxic compounds is absent in biological systems, because the work is done through the agency of biological action.

**Air emissions: prevention or control.** In the case of anaerobic digestion - prevention. In the case of pyrolysis/gasification - control via scrubbers of some sort. Prevention is foolproof; control is not.

**Track record.** The demonstration plant at Hadera routinely processed 11 tons of mixed MSW per day, and in special campaigns as much as 33 tons per day. It operated for two years and, its job accomplished, was decommissioned. The full scale plant at the Tel Aviv transfer station

designed for 220 tons per day was initiated in early 2003, and has now been brought up to full capacity. The system was developed over a 10 year period.

With respect to the track record of UASB digestion - it has been around for three decades and is used worldwide in the treatment of strong wastewaters. In effect, the ArrowBio Process converts the organics in MSW to a strong wastewater.

**Process residue.** Owing to the long solids residence time in UASB (~ 75 days), the solids are necessarily well stabilized and do not require post-AD composting. In fact, the residue would be non-supportive of heat generation and is ready for use as a soil amendment immediately.

**NOTE:** When a composting unit process is part of an AD system, this means that the residue is incompletely digested. The consequences of incomplete digestion are: less biogas, lower quality biogas, and the need for composting with its potential for nuisance odor generation. This is the “red flag” referred to earlier.

**Permitting difficulty/Public acceptability.** We believe the ArrowBio Process is transparently the superior technology with respect to human and environmental health, and that this would be recognized by any would-be opponents of a waste treatment plant.

In summary, the ArrowBio Process has solved the basic problems - up front separation of inorganic and organic fractions, and effective anaerobic digestion through UASB digestion - that otherwise limit AD systems. In other systems, these problems have not been solved.

## FINAL COMMENT

The entries in Table 1, except for the ArrowBio Process, represent different variations on generic themes. It is the commonality among the variations that support the minimal statements made. Specific technologies would deserve independent consideration in, for example, a rigorous evaluation of responses to a well-formulated RFP. Similarly, this analysis could serve as a framework for extended discussion and debate. It is in this spirit that the analysis is offered.

## APPENDICES

### APPENDIX I – THE MOISTURE CONTENT OF MUNICIPAL SOLID WASTE

Numerous factors influence the moisture content of MSW, among them climate, season, weather, local diet and consumer preference. MSW composition studies, not all of which account for moisture, are typically reported in limited distribution reports to the sponsoring agency. Thus, the data on this parameter in the primary literature tend to be scanty, poorly documented, and hard to access.

Exceptional in this regard are three unusually meticulous MSW composition studies conducted by the Edison, New Jersey office of CDM Inc. for three mid-Atlantic counties: Atlantic County, New Jersey; Cape May County, New Jersey; Prince William County, Virginia. The reports are dated 1991. I thank F. Mack Rugg for providing access to these primary reports and for helpful discussions.

Each report documents a county-wide composition study conducted over four consecutive seasons. Curbside collection of source separated items withheld perhaps 20% of the material from the MSW received at the sampling/characterization station. With respect to moisture content, the averages (county-wide for all four seasons) of many composite samples were as follows: Atlantic County, 30.7%; Cape May County, 32.3%; Prince William County, 22.1%. It was suspected that in Prince William County kitchen garbage grinders were commonplace, possibly contributing to the low moisture content of its MSW. Regardless, the overall grand average for moisture content in the three studies was 28.4%.

Various secondary sources tabulate MSW waste composition studies which include the moisture content parameter. In the book by Tillman et al. (Tillman, D.A., A.J. Rossi and K.M. Vick. 1989. "Incineration of Municipal and Hazardous Solid Waste," Academic Press), three different moisture content values are given in three

different tables. The values are: 25.2%, 28.8%, and 31.3%. The book by Liptak (Liptak, B.G. 1991. "Municipal Waste Disposal," Chilton Book Company) provides four values representing different wintertime days. The values are: 27.6%, 34.3%, 25.1%, 22.0%. [Another book ("Hazardous Waste and Solid Waste," 2000. Edited by David H.F. Liu and Bela G. Liptak. Lewis Publishers) tabulates some of the data from the above cited CDM primary reports.] The average of these seven values is 27.8%, or essentially the same as the overall grand average from the three primary reports noted above.

Elsewhere, it is asserted that a good representative value for the moisture content of MSW is 23.2% <[www.epa.gov/epaoswer/non-hw/muncpl/factbook](http://www.epa.gov/epaoswer/non-hw/muncpl/factbook)>. However, attempting to trace the origin of that value through the trail of citations comes to a dead end. The web site document cites as its source: Tillman, D.A. 1991. "The Combustion of Solid Fuels and Wastes," Academic Press. This book indicates that the value came from a composition study in San Diego, California, citing Tillman et al, 1989 (see above). But according to this 1989 book, the origin was a study in Columbus, Ohio. Whatever its origin, the figure appears to be too low to be representative.

It is concluded that for general purposes, in the absence of particular data, 30% may be as good a value as any to represent the moisture content of mixed MSW. With extensive source separation of impervious (glass, metal, plastic) and relatively dry (paper) components for recycling purposes, the moisture content of the remaining mixture would be dominated by food and vegetative wastes. Its moisture content might be 40% or more. Except for extraordinarily successful source separation programs, the remaining mixture would still be the bulk of the waste stream.



## APPENDIX II – UPFLOW ANAEROBIC SLUDGE BLANKET DIGESTION

UASB digestion is not a familiar technology in the MSW field, as it was designed specifically for strong wastewaters. Moreover, this variant is intolerant of particulate matter. Nonetheless, its many advantages prompted Arrow Ecology Ltd. to devise a means of rendering MSW organics amenable to this form of biological treatment. Use of UASB technology for processing solid waste, as in MSW, is unique to the ArrowBio Process.

In outlining the main feature of UASB digestion, it is necessary to use the term *solids* as in the specialized literature. Solids refers collectively to the suspended material in the UASB bioreactor. There are two basic components: the functional microbial community, and recalcitrant, slow-to-degrade, organic substances such as lignocellulose. The community selectively forms itself into discrete “granules” from the array of organisms introduced with the waste. The non-biologically active material may be associated with the granules or in dispersed form.

Each granule is a miniature, mature, ecosystem stepwise transforming organic waste to stabilized solids and biogas, while incidentally liberating the moisture in the waste as liquid water. That is, as solid organic matter is converted to gas, bubbling out of solution, its moisture content is left behind.

The granules and associated solids are kept in suspension to a given “blanket” height, by the bubbling as abetted by pumping.

The essence of UASB digestion then, setting it apart from other forms of anaerobic digestion, is simply put: the solids (read granular microbial ecosystem) and the hydraulic retention times (SRT and HRT) differ greatly. As applied in the ArrowBio Process, these values are approximately 75 days and 1 day, respectively.

Being surrounded by flowing water essentially eliminates barriers to the mass transport of substrate and metabolic end products. In thick slurry systems, such barriers are severely limiting. But in UASB the penetration of substrate into the interior of the microbial granules, and the diffusion outward of metabolic wastes, is greatly facilitated. This significantly enhances microbial efficiency.

A lengthy SRT (prolonged retention of granules) similarly accelerates the rate, and the extent, of the biological

transformation. This accounts for two important attributes: the biogas is unusually methane-rich (~ 75%), and the organic residue is highly stabilized and suitable as a soil conditioner without further treatment. A brief HRT (short residence of a given unit volume of water) minimizes the need for bioreactor volume. This contributes to a modest plant footprint, so that a one module plant (70,000 tpy) requires approximately two acres.

Operationally, excess water with entrained growths (microbial granules proliferate at expense of the waste) is transferred to a settling tank. Supernatant is pumped to the physical separation/preparation element (“water vat”) as needed for makeup water, or to an aerobic tank for polishing if necessary. Water may be stored or used immediately as in irrigation. The solids are dewatered for use as organic soil amendment. Owing to the lengthy SRT hence substrate depletion, there is no need for additional treatment. The biogas collects in the head space of the digester and from there goes to use or storage.